Chapter 13
Concept Design

Introduction

In this chapter, we will explore potential applications and then discuss preparation of concept designs.

To date, the use of WIG craft has been restricted to prototype trials and test operations, mainly for military and paramilitary purposes. In Russia in particular, as described in Chapter 2, the navy invested heavily during the 1960s and 1970s in a succession of craft. The initial series of pure trials craft lead to design of larger vehicles suitable for fast logistic service for the Russian Navy in the Caspian Sea. These developments and operations demonstrated the effectiveness of the technology and gained valuable practical experience.

The Russian programme has been followed by a more recent WIG development programme in China aimed at medium-sized craft effective for utility or ferry service. Many lessons have been learned already in this programme about improved efficiency. The deployment of coastal patrol WIG craft is the next technical objective and will also be attractive to many other coastal and island nations in the Far East for combating piracy and smuggling.

If this knowledge can be put to use in the development of medium and large craft aimed at commercial duties, there is also the potential to fill a gap in the transport spectrum between fast marine ferries and cargo aircraft in the near future.

At the smaller end of the scale, prototype WIG craft with a wide range of lifting surface geometries have been built in countries ranging from Australia and China to Germany and the United States. The technology is continually being advanced, mainly by private individuals and small private companies. There is a substantial potential market for such craft, once the hurdle of acceptance of a new technology has been overcome.

Since the late 1990s, the WIG concepts developed at RFB in Germany have been taken over by Flightship in Australia (later moved to Singapore ownership and location) and further evolved into craft that are economic for air taxi services. The craft have been certified under the IMO and Australian regulations for operation, so may be considered the first major breakthrough into commercial operations for WIG.

L. Yun et al., *WIG Craft and Ekranoplan*, DOI 10.1007/978-1-4419-0042-5_13,

So, what are the key WIG attributes? They may be characterised by

- High service speed: The craft take off from the water surface and are fully aerodynamically supported during normal service operations, so hydrodynamic drag is small compared with conventional high-speed ferries and military craft. WIG are able to operate economically at speeds from 100 up to about 500 kph, a region currently possible only with aircraft.
- Seakeeping quality: Since the craft fly above the sea surface, seakeeping quality is high compared with other marine craft, and there is only small speed loss in a seaway. The sea state for take-off is more restrictive and so relatively sheltered conditions are necessary, together with service routing across sea areas with limited extreme sea states, for example, coastal areas, inland seas and the equatorial oceans.
- High work capacity: There are no particular difficulties to develop very large WIG, for example, as large as 5,000 t displacement, 500–1,500 t payload, 400 km/h and 2–10 m flying height. Conventional aircraft are very costly to scale up this far due to the limitations of available airport runways. Medium-sized WIG have potential work capacity that is larger than conventional high-speed marine vessels, due to their higher service speed and lower speed loss in a seaway.
- Marine terminal/base facilities: WIG craft can take off from the water surface and so do not need a prepared runway or airport-type facilities. So long as the craft is designed for manoeuvring in the floating condition and there is a suitable take-off area close to the terminal where other marine traffic can be controlled, such craft can operate in a similar manner to high-speed ferries or seaplanes. Many of the world's larger cities are located in river estuaries or at a coastline, so development of useful "Blue Highways" may help to lighten the road and air commuter-based traffic in the future for medium distance operations and offer an intermediate-speed freight service on intercontinental routes.
- Safety: WIG craft operate close to the water surface and in the strong surface effect zone during take-off and touch down. The design of lifting surfaces for take-off and normal flight provides a stable response in ditching, so WIG craft can be designed for safe landing in case of engine failure, with a softer landing than normal aircraft in such conditions.
- Low fuel consumption: Since WIG are operated in the surface effect zone, aerodynamic efficiency is high, so reducing fuel consumption to less than half that of an equivalent aircraft.
- Construction: WIG craft are classified as a marine vehicle through IMO rules, so the requirements for qualification of craft construction and the equipment on board are different to that of an aircraft. Prototype development costs should be limited, following marine practice rather than that of the aeronautical industry. Construction cost will be in between the level for a fast ferry and a turbo-propeller aircraft.

From Fig. 13.1, it can be seen from the relation between speed and craft weight that the ideal application for WIG is located between the aircraft and conventional high-speed marine craft, such as ACV, SES and hydrofoils.

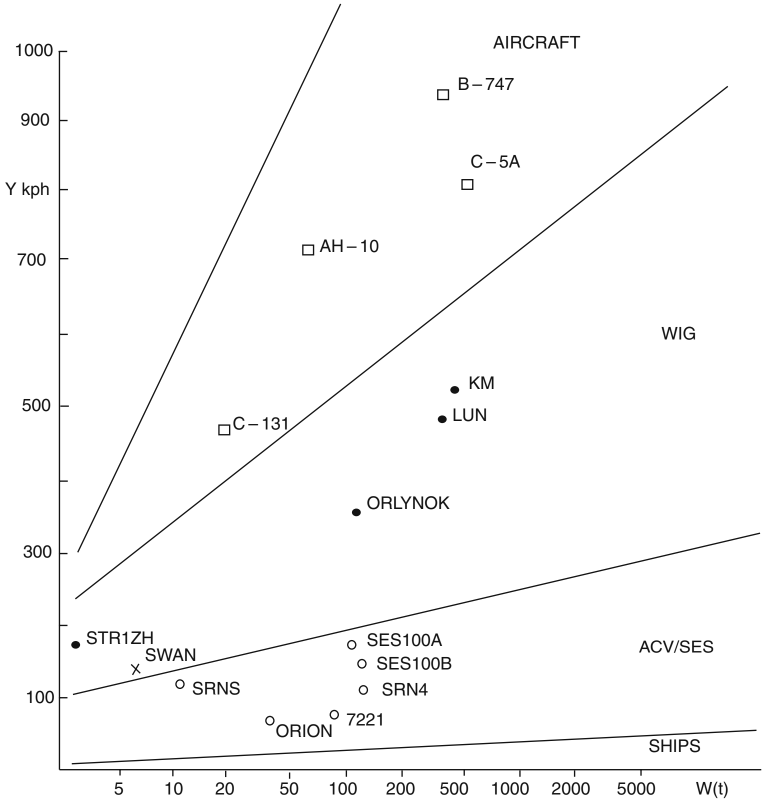


Fig. 13.1 Application zone for various craft max craft weight and speed

Figure 13.2 shows the relation between the speed and lift/drag ratio of various vehicles (figure appears wrong – need careful data check – e.g. helicopters – think labels are just mixed up).

Figure 13.3 shows the specific power, i.e. engine power over vehicle weight (horsepower/tonne) plotted against vehicle speed, for different lift–drag ratios. It can be seen that WIG are an efficient means of transport at speeds of 150–500 kph both at small and large sizes.

Figure 13.4 also shows the relation between the specific power and maximum cruising speed. The specific power of WIG in this figure is much higher than that in Fig. 13.3 due to the different source of data. There is a considerable variation in the absolute values of such parameters found by engineers working with different design styles for WIG.

Figure 13.5 shows the required power for different transport vehicle types. The co-ordinate P/W is normalised to the power of a standard automobile at a speed of 100 kph. This figure suggests that the optimum for WIG is 150–400 kph. In general, WIG are found to be most efficient at this service speed range, while the limitation for all up weight is determined by available propulsion power plant.

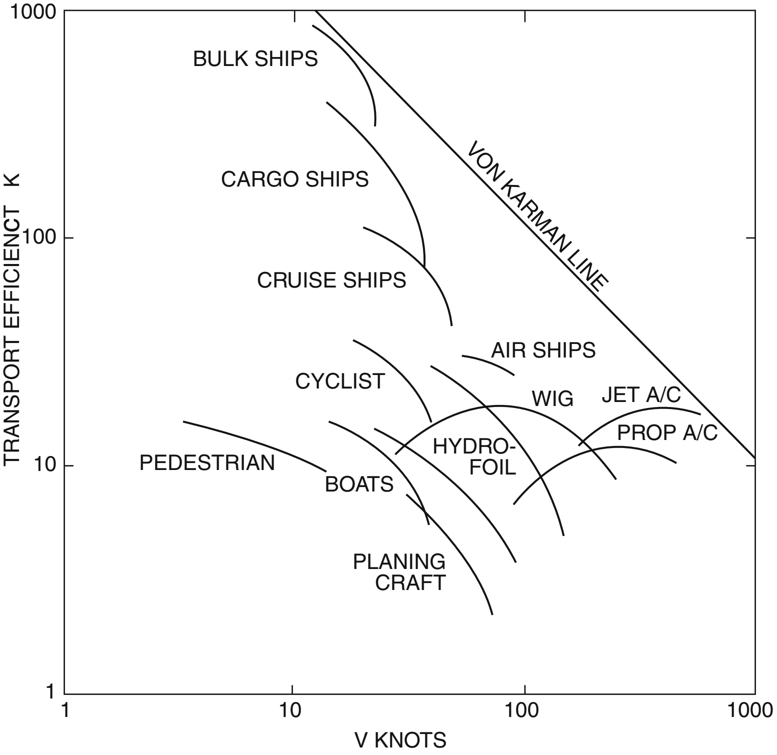


Fig. 13.2 Lift versus speed for various transport

General WIG Application Issues

There are no WIG commercial service routes operated so far, even though the WIG has been successfully operated and tested for more than 30 years. While technically successful, development of the support systems for WIG commercial operation will require significant investment in terminal facilities similar to large amphibious hovercraft terminals. References [1–3] provide background information on operational considerations and route selection based on current available craft.

Successful operation of small-scale operational trials are likely to be necessary, rather like the ACV passenger operations in the 1960s with SR.N6s that provided the encouragement for the cross-channel SR.N4 ACV ferries. The following main aspects need to be further improved compared to prototypes constructed to date:

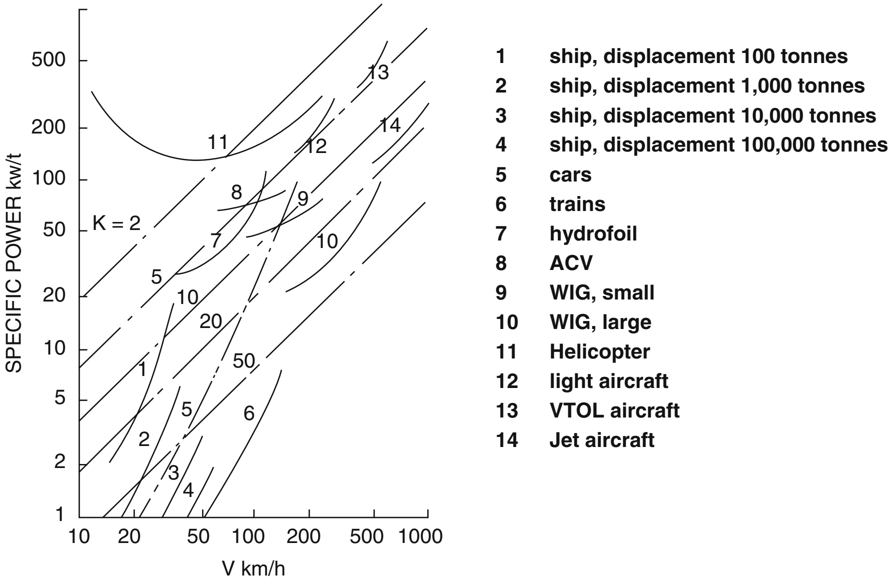


Fig. 13.3 Specific power versus speed for various transport

Technical Factors

- *Take-off*: The take-off speed of a WIG without lift enhancement is high due to its high hump speed. Reducing the hump drag and take-off speed so as to reduce take-off and overall installed power requires a PARWIG or DACWIG design. On PARWIG, the bow lift enhancing blowers may shut down after take-off, but become excess weight during cruise. Small WIG may be designed with lighter wing loading so as to reduce take-off speed, but this limits the cruise speed attainable. Air cushion systems can be very useful for lowering take-off speed, but require incorporation of flaps and perhaps other means to change the main-wing profile after take-off so as to enable high cruise speed. Active control surfaces have the penalty that they require constant adjustment in flight, placing a high demand on the pilot.
- *Stability*: Automated control systems for WIG will be more complicated than that on an airplane or hydrofoil craft, because the WIG has to assure its safe operation while at great speed very close to the surface. At present, there are no commercial systems available that are suitable for high-speed WIG autopilot service, and so all designers of WIG, small or large, have to aim at a craft that is statically stable and have a stable response to dynamic controls in flight, so that the pilot can fly the craft manually in a safe manner.

Aerodynamic efficiency: The aerodynamic efficiency *K* increases with aspect ratio; however, the main wing lift force during take-off increases inversely with

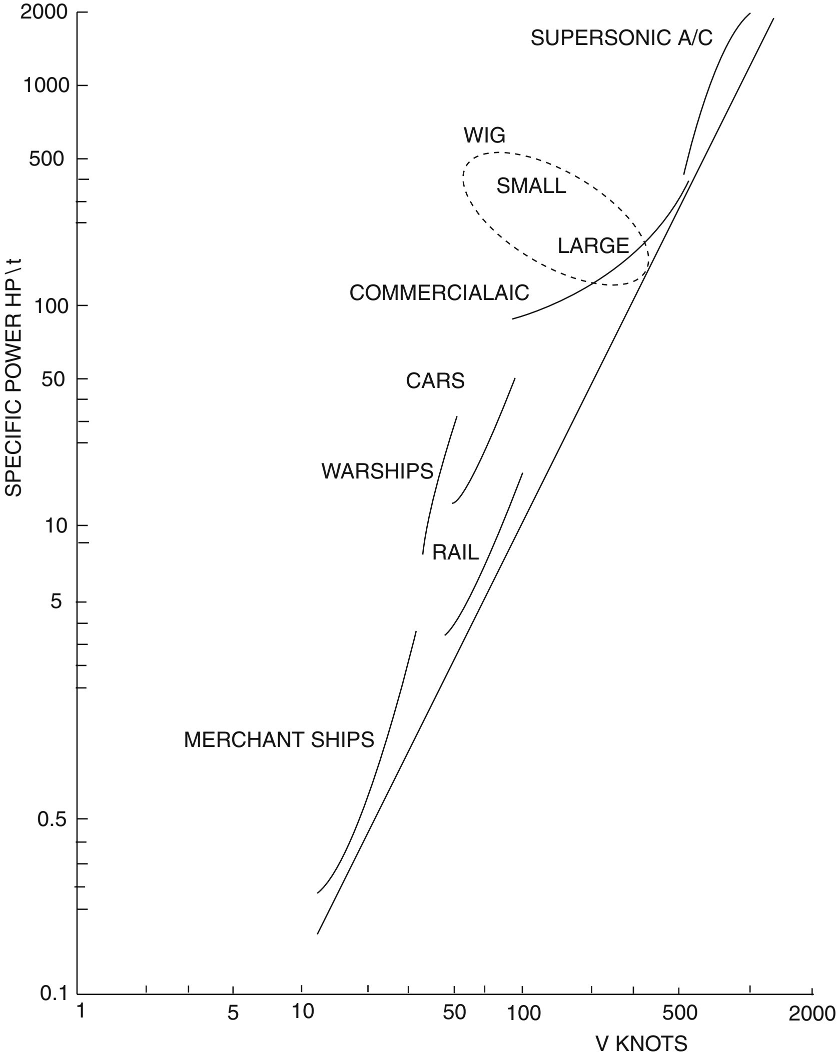


Fig. 13.4 Specific power versus maximum cruising speed as a function of installed power for propulsion and gross weight (displacement), compared with state of the art line defined by G. Gabrieli and T. Von Karman

aspect ratio. The best way to solve this problem is to use a composite wing with AR = 0.5–0.8 for main wing and AR = 3–4 for the extended wing. In addition, the main-wing plan form needs careful design. WIG targeted at cruise speed up to 300 kph can employ a strongly tapered wing with anhedral and washout to improve static stability through the speed range. High-speed craft require a more rectangular main wing with careful attention to flap design for low-speed operation.

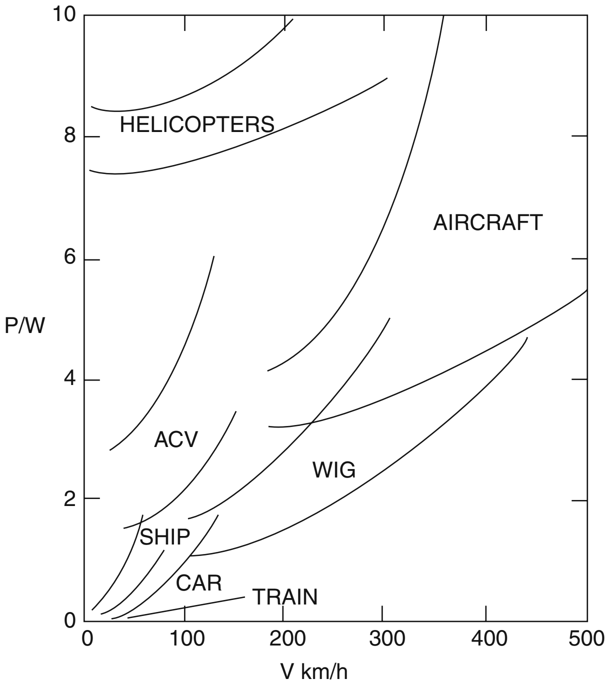


Fig. 13.5 Required power for different transport vehicles

Operational Factors

- *Terminals*: A WIG operation will need to be near coastal cities, similar to existing ports designed for ships and boats. WIG facilities needed are similar to a Hoverport for amphibious hovercraft with entry and leaving slipways and a large manoeuvring apron, see [4]. Deep water is not required, rather, and area outside normal navigation channels suitable for a water runway of 1,000–2,000 m in length and 500 m in width.
- *Manoeuvrability*: WIG are difficult to operate alongside other craft or a quayside due to their protruding main and tail wings, so terminal operations need an approach similar to amphibious hovercraft. Design of low power water thrusters for floating manoeuvring of WIG up to the slipway is an area requiring development so as to avoid excessive use of main engine power close to a terminal. The DACWIG and DACC are able to manoeuvre on their air cushion at slow speed, so do not have the same design constraints. During flight all WIG require more space to manoeuvre than an ACV simply due to their higher speed. While many WIG can bank into a turn, the reduction in manoeuvring space does not change the overall requirement. WIG navigation therefore needs to be separate from other marine craft. Due to its speed, a WIG has to be operated on the basis

that it is invisible to all other craft and ensure that it takes collision avoidance action, including maintaining a safe distance from other craft of (for example) between 1 and 5 km depending on speed.

- *Safety*: The collision risk for WIG is higher than that of conventional high-speed craft because of its very high speed and operation essentially at ground level, so the navigation equipment installed such as radar has to be responsive, precise, light and reliable. In addition, the requirements for the equipment used in navigation ground stations at terminals are also rather higher than normal for ferries or aircraft.
- *New technology*: The WIG is a new vehicle type operating at high speed essentially on the water surface, so both aircraft pilots and captains of high-speed marine craft have little applicable experience. For aircraft pilots, flying close to the ground, with manoeuvring available only in the horizontal plane and little possibility to bank, is a major challenge. Using the "Jump" technique for collision avoidance is also a very special driving method, requiring practice. For a marine captain, the extreme high speed requires a different approach to normal marine craft. Clearly therefore, setting up operations with a WIG service will require considerable vision on the part of the operator and careful training of personnel.
- *Noise*: For a current generation WIG, the noise pattern is similar to a turbo-propeller aircraft operating close to the water surface. Ducted propulsors are a help to reduce noise signature, similar to the ducted propulsors on modern ACVs. However, since the water surface absorbs some noise and as the WIG is always operating in GEZ influencing the noise dispersion, the actual noise pattern should be lower than aircraft with the same power. There are few investigations about this so far due to most WIG craft being built for military duties. It is likely that noise close to terminals, i.e. slow-speed manoeuvring noise, will be the controlling factor to acceptance, both by travellers and the communities around the terminals. Adoption of ducted propulsors, and high bypass turbofans on larger craft should allow design to acceptable criteria.
- *Economy*: Figure 13.6 shows the aerodynamic properties of WIG in both first and second generations, and airplane weighing 450 t [5], where 1 – first-generation WIG, 2 – second-generation WIG, 3 – airplane, $K_{\max}$ the maximum aerodynamic efficiency, h the flying height and C the wing chord. The figure shows the $K_{\max}$ of second-generation WIG can exceed airplane transport efficiency. Figure 13.7 shows the WIG weight composition compared with aircraft, where W_{p} and W_{f} represent the payload and fuel weight, respectively, and W craft take-off weight. WIG have a lower payload weight fraction due to their marine construction. Figure 13.8 shows the comparison of fuel consumption of WIG with an airplane, where R represents the range. From these figures, one can see that the second-generation WIG can begin to compete with large jet aircraft. It is proposed nevertheless that the WIG at present are more suitable for short-range routes of 100–400 nm length, on which aircraft are less efficient due to the many take-off and landing operations.

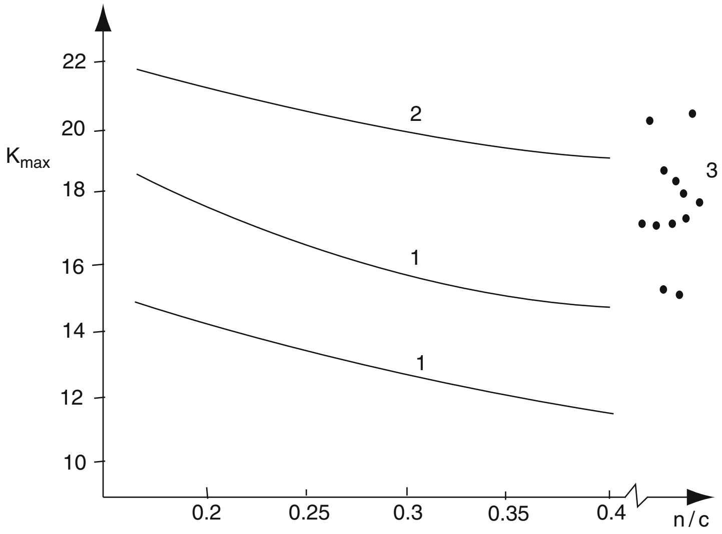


Fig. 13.6 Aerodynamic properties of first- and second-generation WIG

WIG Subtypes and Their Application

The WIG concept includes a range of subtypes as has been discussed through this book. Each has its own potential niche in the transport spectrum, as introduced in Chapter 1. General attributes affect the specification and design of all types of WIG and so should be considered first are as follows:

- As the craft will not be operated at high altitudes, the fuselage (or cabin) of the craft need not be constructed for pressurisation, as for commercial aircraft. On the other hand, since most operations will be over salt water, the structure must be watertight and resistant to salt water corrosion.
- The navigation of WIG is different from that of conventional marine craft. The WIG can be operated across shallows and does not need marked channels by water depth or pre-designated navigation routes. Tidal conditions are also no problem if a slipway and hard standing terminal apron is used.
- Terminal equipment has to be similar to that at airports for seaplanes, or a Hoverport, and provide for:
  - Embarkation and disembarkation safely of passengers from/to shore
  - Loading and unloading fuel, fresh water and provisions
  - Radio communication over the service routes
  - Provision of weather, and sea state and marine traffic data along the route
  - Equipment and systems maintenance and support for pre-flight preparations.

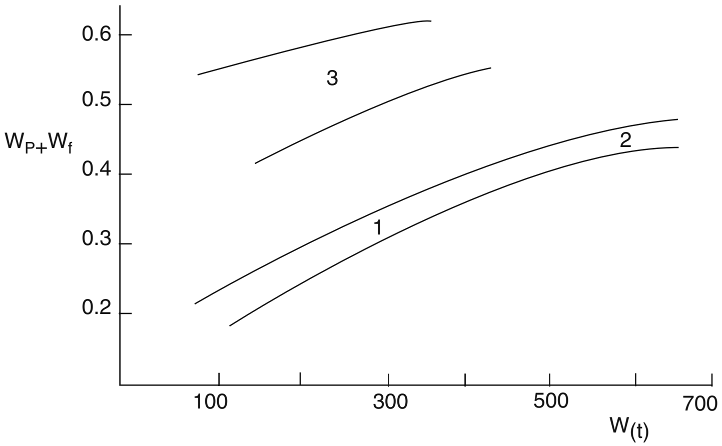


Fig. 13.7 Weight composition of WIG

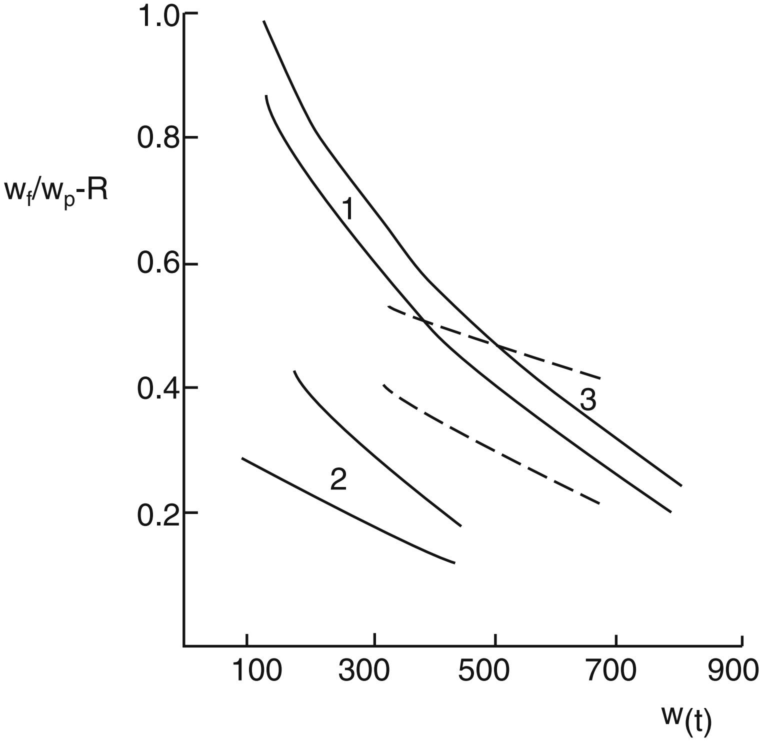


Fig. 13.8 Fuel consumption of WIG

In addition, the following has to be prepared for WIG passenger routes:

- WIG operational support including terminal and cabin staff, and handling of passengers and luggage
- Technical service and maintenance organisation, facilities for crews and passengers, take-off "runways", landing slipways and manoeuvring aprons
- Operational communication with the WIG vehicles in service and call up of equipment for service support
- Wind and wave data on the route, e.g. sea state and wind occurrence, direction and persistence

For successful and safe commercial operations, the route of an established service should be designated as a WIG route and documented on charts so that ships would be warned of the presence of these high-speed craft. There are rather different requirements for navigation between conventional ships, ACV, hydrofoils and WIG. These differences and the expected behaviour of other traffic when faced with WIG in the same area will need to be communicated to other marine traffic in the marine pilot handbooks for the locality.

WIG Preliminary Design

In the following sections, we will introduce a suggested procedure for WIG preliminary design, using comparison with other high-speed marine vehicles as a starting point. In general, the overall design of WIG is similar to conventional high-speed marine vehicles; however, there are some differences:

1. *Modes*: There are several operational modes to analyse, such as floating, air cushion borne and flying operation over ground, calm water and in waves. Both hydrodynamic and aerodynamic performance analysis has to be performed and balanced.
2. *Dynamic stability*: The PARWIG and DACWIG operate close to the water surface, in the strong surface effect zone without direct contact. Dynamic stability has to be provided from aerodynamic forces alone. This is different from conventional fast marine craft or so-called dynamic supported craft such as ACV/SES/hydrofoil/catamaran, which interact with the water surface itself.
3. *Water impact loading*: The craft will interact with waves in extreme sea states; hence wave impact loads on the hull and side buoy structure have to be taken into consideration. WIG craft speed is much higher than conventional high-speed craft, so the impact loads are increased.
4. *Low-speed manoeuvring*: It is difficult to employ flexible skirts as on amphibious hovercraft, or retractable landing gear as on aircraft, for a WIG without compromising the cruise speed or requiring complex retraction systems, so the design

of a cushion system and landing pads or wheels requires careful specification for manoeuvring and support at the operational base.

5. S*tructural design*: The hull and wing has to meet a compromise between conflicting requirements of low weight against a rather large specific area of shell plating and high structural loads on the underside of the hull and floats, similar to a flying boat. A DACWIG craft has multiple "hulls" to design and optimise. Figure 13.9 shows a transverse section of various high-speed marine vehicles. There are two sidewalls on a conventional monohull and hydrofoil, four sidewalls on catamaran and SES, six sidewalls on DACWIG type 1 (i.e. the craft with two air channels) and ten sidewalls on DACWIG type II (craft with two air channels and one mid airfoil). More hull weight is dedicated to the sidewalls as the configuration becomes more complex. A comparison of the specific area of various high-speed marine vehicles is shown in the following table:

	Monohull	Hydrofoil	SES	ACV	WIG
Specific area	10	10	13	21	28–35

Where Specific area $= S/\nabla^{2/3}$

S Area of shell plate and framework (m^2)
∇ Volume displacement of the craft (m^3)

6. *Machinery*: The air propellers and power plant are to be installed on the craft taking into consideration water spray (operating in waves during take-off), weight, potential corrosion and erosion by mud (if operating over ground), and potentially long power-transmission shafts.
7. *Construction*: WIG craft structural design includes elements of both marine craft and aircraft design, so where should it be constructed, in a shipyard or aircraft plant? This is still a strong debate in the WIG design community.
8. *Safety and certification*: Which organisation will be responsible for policing the IMO code of safety and operation [6] for WIG within nation states? This is still a problem that has not been finally clarified, though ship classification societies such a Germanischer Lloyd and Lloyd's Register have taken a lead so far.

Design Sequence

WIG design should follow the overall sequence below:

(i) The determination of specifications, design standards and criteria, safety code and some requirements for the overall design of WIG, such as:

- Specification of functional requirements (see 1. below)
- Inclusion of performance-related design requirements (see 2. below)

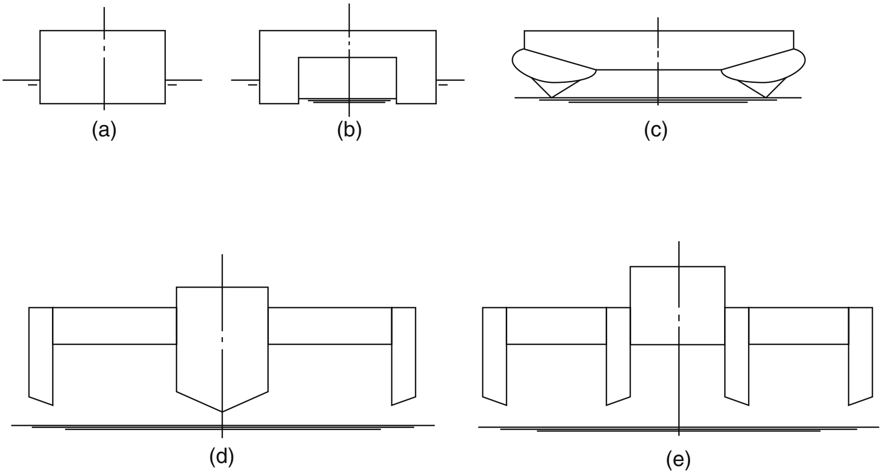


Fig. 13.9 Transverse section sketch for various high-speed marine vehicles

- Inclusion of relevant safety code requirements for the WIG (see 3. below)
- Inclusion of requirements for amphibious capability (see Chapter 5)
- Specification of main dimensions;

(ii) The determination of aerodynamic configuration and principal dimensions.
(iii) Model experimental investigation of the aerodynamic and hydrodynamic of WIG (see Chapter 9).
(iv) Initial design establishing structural configuration, main machinery selection, configuration of cargo spaces, control surfaces, fuel tankage, etc.
(v) Determination of craft cost, operational economics, construction planning, etc.
(vi) Detailed design.
(vii) Operations and maintenance guidelines and manuals.

Functional Specification for a WIG

First we set up a typical specification for a passenger WIG. References [1, 7, 8] provide additional material that may assist this process. The designer should identify his requirements for the parameters outlined below, taking guidance from the theory chapters of this book presented earlier and making reference initially to craft of similar specification that have already been built. The designer should expect to make two or three successive estimates for the different parameters, since initial choices may be incompatible. As experience is gained, a design selection will be closer to a practical data set in the first cycle!

1. *Specify the craft mission*: Function (passenger, freight and military duty), normal route or operational area and range, cruising operation speed and desired mode.
2. *Specify desired calm-water performance*as follows:
    - Maximum flying speed at normal displacement and flying height
    - Cruising speed and flying height
    - Desired range at cruising speed
    - Target take-off speed and time as well as distance
    - Target touch down-to-stop distance (inertia of the craft)
    - Minimum turning diameter with rolling angle when hull borne, cushion borne and in flying mode
    - Jump (permitted or not), jump altitude desired
    - Desired draft in hull-borne mode
    - Requirements for compartmentation and reserve buoyancy from IMO requirements, etc.
3. *Specify desired performance in waves* (seaworthiness) at normal displacement
    - Take-off and touch down at maximum significant wave height and wind force
    - Target cruising speed and maximum speed at maximum significant wave height and wind force
    - Flying height at above-mentioned speed
    - Minimum turning diameter in the various operation modes in waves
    - Jump possibility (normally same as over calm water)
4. *Specify desired amphibious capability*: With exception of DACC, which may be designed with mission requirements similar to an ACV, DACWIG use their cushion system primarily to improve take-off and landing and allow manoeuvring at a terminal [4]. The DACC may need to consider its mission terrain and design the skirt system accordingly, while the DACWIG needs only to consider the smoother terrain of a concrete apron and launch ramp curves.
    - Possibility of hovering up landing ramp from water surface
    - Landing ramp slope
    - Dimensions of landing area
    - Condition of landing area
    - Obstacle clearing ability of the craft, height and terms of obstacles
    - Ability for passing across ditches or other obstacles, its width and depth.
    - Performance over rough ground, estuaries, everglade areas, etc. (DACC)
5. *Specify passenger accommodation and freight payload*:
    - Seat number and requirements
    - Accommodation of passenger cabin

- Requirements for comfort, noise level, acceleration level and vibration in passenger cabin
- Safety equipment
- Luggage and equipment storage
- Freight volume and weight, loading container design

Carriage of freight aboard a WIG will be most conveniently loaded on standard air freight containers for medium-sized freight WIG. If operations are associated with a coastal airport, the freight service will be able to be linked in with its infrastructure for freight forwarding, so optimising container usage. Large WIG are more likely to base freight carriage on palletised units that can be transferred into standard rail or road containers, or Ro–Ro trailer units. Data for both these freight carriage forms are available from the air freight and sea freight industries.

6. *Make preliminary choice of WIG type*: The craft type and aerodynamic configuration can now be selected, such as

   - aircraft type layout with trapezium-shape wing (Russian PARWIG type Orlyonok) or
   - aircraft type layout with straight square-cut wing (Russian Ekranoplans) or
   - aircraft type layout with rectangular wing (typical for dynamic air cushion craft type such as Volga-2) or
   - aircraft-type layout with rectangular main wing and trapezium composite side wing, so-called DACWIG, etc. or
   - forward swept and tapered wing such as flightship craft

7. *Select principal dimensions and estimate weight*:

   - Payload: weight of cargo, passenger seats and their luggage
   - Maximum take-off weight: use a rule-based multiple of the payload initially
   - Length overall: select based on take-off weight and the mission parameters
   - Width overall: main-wing span and chord based on chosen WIG type
   - Maximum height: tail height based on fin area requirements and propulsion engine/propeller dimension

8. *Select main machinery*:

   - Bow engine (lift engine, type, maximum take-off and rated power, revolution, specific fuel and oil consumption, etc.) and its driven air propeller, as well as power transmission
   - Stern engine (propulsion engine, type, maximum take-off and rated power, revolution, fuel and oil consumption, etc.) and driven air propeller
   - Pitch adjusting mechanism for both bow and stern propellers
   - Air propeller ducts, if applicable

9. *Select auxiliary machinery*:
    - Hydraulic system for driving rudders, flaps and guide vane after bow propellers of bow thruster itself, etc.
    - Electrical power plant and equipment
10. *Select navigational, communication and automatic control systems*:
    - Navigational complex and separated navigational devices
    - Radio engineering collision warning and above-water surroundings display system
    - Centralised control system for communication complex
    - Inter-crew communication devices
    - Automatic pilot system
11. *Select hull, wings and stabilisers material and construction:*
    - Hull material and construction method
    - Material of main wing, composite wing and vertical as well as horizontal fixed stabiliser and their construction methods
    - Material for vertical and horizontal rudders and their construction methods
    - Material for side buoys and their construction method
12. *Specify other equipment*:
    - Material and construction method for landing pads or alternative landing undercarriage
    - Life-saving equipment
    - Fire detection and protection equipment

Preparation of this base data for the craft design then enables the designer to begin drafting out the craft geometry, and beginning the procedures outlined below to analyse the craft characteristics and performance, and adjust the parameters until they are in balance.

Design Requirements

Before proceeding into preliminary design for our WIG, we have to select some further design parameters that will set the requirements for overall geometry and compartmentation of the craft. Once these requirements are set, the influence of IMO and Classification Society criteria can be assessed, as outlined in Section 3 below.

1. *Requirements for intact stability*

    (1) Floating and cushion-borne stability can be calculated by the same method applied for conventional high-speed craft. The requirements for initial stability and stability at large heeling angle are the same.

(2) Longitudinal stability requirements in flying mode are see [8]:

$$\bar{X}_{F\vartheta} > \bar{X}_{F\bar{h}} > \bar{X}_G \text{ and } \bar{X}_{F\vartheta} - \bar{X}_{F\bar{h}} = 0.1\text{–}0.15 \quad (13.1)$$

$$\text{Or} \qquad \bar{X}_{F\vartheta} > \bar{X}_{F\bar{h}} = \bar{X}_G \quad (13.2)$$

$$\bar{X}_{F\vartheta} - \bar{X}_G > 0.03 - 0.08 \quad (13.3)$$

Where

$\bar{X}_{F\vartheta}$	Relative position of trimming centre
$\bar{X}_{F\bar{h}}$	Relative position of heaving centre
$\bar{X}_G$	Relative position of centre of gravity of craft (*X*/*C* from wing leading edge)

The physical explanation for these relations can be described as follows:

1. In case of head wind, the craft will rise up with a slight of decrease in the trim angle and also
2. In the case of the craft descending in altitude, lift will be increased and acting at heaving centre, behind the CG, causing trim angle to decrease; however, since the pitching centre is behind both the heaving centre and CG, and with a negative pitching moment acting, so the trim angle will increase a little and finally cause the craft to descend stably
3. For the same reason as in 1 and 2, the craft can also climb stably

On many WIG, $\bar{X}_{F\vartheta}$ decreases with increasing ϑ, but $\bar{X}_{F\bar{h}}$ increases with increasing ϑ, so in the case of trim angle greater than critical trim angle, the $\Delta\bar{X}_{F\vartheta\bar{h}}$ will be negative and may cause overturning backward (bow pitch up). This situation is most dangerous for WIG. In general, $\vartheta_{critical} = \sim 5 - 7^0$. Therefore, pilots should be careful to avoid running at trim angle close to $\vartheta_{\text{critical}}$ and designers should try their best to make critical trim angle as high as possible.

Relation (13.1) gives the criteria for positive longitudinal stability. Achieving (13.2) will ensure that small gust disturbance leading to a positive increase of flying height will not disturb the craft trim angle severely. Equation (13.3) defines minimum reserve values for the longitudinal stability.

It may be noted that these criteria are somewhat tighter than the recommended values from the original Russian trials programme and represent the needs for a craft that has to meet criteria suitable for hovering as well as flying. However, the difference between the trimming centre and heaving centre cannot be too great, as it will cause a decrease of pitching decay coefficient, so as to reduce the longitudinal dynamic stability. Perhaps this is why the aerodynamic configuration design for longitudinal stability of a WIG is so difficult.

2. *Requirements for damage stability*

The requirements for damage stability are similar to the requirements for conventional high-speed craft [6, 9, 10]. According to the safety code issued by IMO, if a craft is damaged, it should maintain

- Positive buoyancy and the minimum distance between the damaged condition water line and main deck (or holes on the side plate of hull) should be greater than 76 mm
- Positive static hydrodynamic stability
- The calculated flooding conditions are
- One cabin (or compartment) either in hull, side buoys or in main wing, flooded with a total length equal to the largest single compartment, or 20% of the hull, buoy or wing length for smaller craft, whichever is greater

Two adjacent compartments flooding with same condition as above, for larger craft.

3. *Restrictions on overall dimensions*

The principal dimensions may be constrained by the following functional requirements:

- Interface to terminal facilities for passengers or freight
- Landing area and slipway geometry
- Workshop or covered storage of the craft
- Bridges or other physical obstacles along the service route
- Width of rivers used for service route, etc.

Detachable structures and/or foldable composite geometry wings may be useful for accommodating restrictions at the terminal or maintenance base. Obstacles or restrictions on the service route itself have to be accommodated by the craft's overall design. Bridges and narrow parts of a route may be approached at lower speed and restricted flying height.

4. *Requirements for seakeeping safety*

*Steady operation over waves:*Analytical methods for predicting craft safety in a seaway are still difficult. However, some experimental investigations can be carried out during the design stage as follows:

- Radio-controlled self-propelled model tests over open water can be used for estimating qualitatively the safe operation of the craft at various wind/waves force and directions, including take-off and ditching
- Model tests in a seakeeping tank with various wave/wind directions and force for determining quantitatively the model stability, also including ditching

The tests mentioned above mainly check the stability of the craft and the possibility of immersion of bow thrusters into the water, which is a most dangerous occurrence.

Existing experience [11] suggests DACWIG craft can operate safely if the following equation can be satisfied:

$$H_{\min} = 0.5 + 0.2.H_{\mathrm{w}} \tag{13.4}$$

Where

H_{w} Design maximum wave height for operation (m)
$H_{\min}$ minimum safe height at which WIG can fly (m)

Or $H_{\mathrm{m}} > (0.6-0.7)\,H_{\mathrm{w}}$, where H_{m} is minimum safe flying height over a seaway

Take-off over waves: A very important criterion for craft safe operation in waves is the ability to take-off. Sufficient reserve power for both lift and propulsion engines have to be accounted for in design. Seakeeping tests of a model in a towing tank to predict the additional wave drag are very useful. The lower the cruising speed, the more important are tests, as the craft drag at take-off speed being the controlling factor for installed power rather than power needed to maintain cruising speed in such a case.

Slamming loads: Design of the under body shape of main hull and side buoys should follow marine and seaplane practice so far as possible, using inclined planing surfaces, curved rather than straight planes and preferably two or three steps in the main hull. This approach will help to minimise the drag hump and reduce slamming loads in the seaway during the take-off and landing runs.

5. *Requirements for habitability*: The ride for WIG in flying mode is smooth and so internal craft vibrations due to the main engine and transmission will be the main issue for passenger comfort. During take-off the ride will be somewhat bumpy, so that all personnel should be seated and strapped in, similar to aircraft take-off. Provisions, luggage and cargo should also be locked down or in lockable containers/compartments.

   The following points should be considered in addition to the general requirements for the habitability of conventional fast marine craft. Analysis should be carried out for two key conditions, waterborne just prior to take-off in the design limiting seastate and the ditching condition into the limiting seastate.

   - *Vertical acceleration* in passenger cabins running in waves has to satisfy ISO2631 for passenger comfort.
   - *Internal noise level* in passenger cabin: Passenger cabins are generally surrounded by both lift and propulsion engines, so internal noise level will be unacceptable unless care is taken to install sound isolation in the rear (and possibly front) bulkhead and also the main fuselage shell. The standard for the internal noise level has to satisfy the rules issued by the classification society or the requirements demanded by operators, typically below 80 dBA. Noise is much less of a problem once flying, nevertheless the direct impingement zone from propellers (in line with the blade disc and a cone from directly behind) needs to be protected. Ducted propulsors are useful as the duct itself can be used as a sound absorber.

- *External noise:* The external noise level of a WIG is less than an aircraft because it is localised by its proximity to the water surface as a sound-absorbing barrier. The criteria for acceptance of WIG operating close to cities will be rather more stringent than for aircraft. Typically, 95 dBA at 100 m distance should be a target for smaller craft and the same level at 300 m for larger craft.
- *Field of vision* for pilots, navigators and passengers: This is strongly affected by spray generation during take-off and operation in waves, and the navigation cabin arrangement, located between the wings, which is rather different from the arrangement on other high-speed craft. The poor field of vision for pilots and navigators increased the difficulty of handling of early WIG. Use of video cameras for side and rear views can improve this at low cost on modern craft. Passengers will be more comfortable and less susceptible to travel sickness if windows allow good vision outside so as to maintain a steady sight horizon. WIG unsteadiness in roll in the higher GEZ makes this an important area to achieve the correct balance of design for the craft layout.

6. *Terminal requirements:*In order to ease landing and manoeuvring at a terminal, it is suggested to design terminals as follows:

   - *Slope of ramp for landing*: Depends on craft size. For small craft a slope of 5–15° is negotiable without trouble, while for larger craft a slope of 5° or less is preferred.
   - *Number of ramps*: If one craft only is likely to be arriving or leaving at one time and the local wind conditions are consistent, then a single ramp may suffice. Where multiple craft will operate together and/or the wind conditions can change direction significantly, then a second ramp oriented 60–90° apart will assist operations considerably. The manoeuvring apron will also need to be rearranged to allow craft to access either ramp from its loading station or dock.
   - *Manoeuvring apron*: This is also craft size dependent and relates to the number of craft expected to be resident at any one time. For a single craft operation, an apron of about three craft lengths square will be acceptable, including the loading station area or docking station. Care must be taken to orient the loading station so that craft can approach into wind.
   - *Maintenance and storage*: Craft are likely to need a maintenance facility together with the terminal. This needs to be located outside the manoeuvring area and include a lightweight hangar since major maintenance operations will be associated with main engine and transmission overhaul, control systems and propellers.
   - *Passenger and freight facilities***:** Passenger facilities for WIG terminals will be similar to air taxi terminals at an airport for taxi services, Fast Ferry or Hovercraft terminals for larger scale passenger operations and to air freight terminals for freight services.

Safety Codes for WIG Craft

Where WIG are used as passenger transport, the safety code introduced by the IMO forms the basis for our design criteria. Here we introduce briefly the safety code for WIG issued by IMO in 2000 and offer some additional suggestions. WIG for freight should also consider the IMO requirements as well as the normal International Regulations for maritime traffic. Small WIG will be exempted from a number of the requirements, partly due to size and partly due to their more limited range of operation.

Basic Concepts

1. *International regulations*

   The following aspects of operation are taken into account:

   - Start and landing of WIG is carried out on the water surface.
   - Operation is close to the surface of the water.
   - Possibility to jump up to overcome or over-fly obstacles is limited to a transitory mode. The height of such jump up is much smaller (a few metres only) and does not come within the altitude foreseen for the normal operation of aviation transportation covered by general aviation classification requirements.

   The IMO definition, agreed with the ICAO is as follows:

   "A WIG craft is a multimodal marine craft capable of operation in a mode where the craft is supported wholly in the air above water or some other surface, and not having constant contact with such surface, through the use of an aerodynamic lifting force known as ground effect. Ground Effect is generated during forward movement of the craft by interaction between the lower surfaces of the crafts wing (wings), hull, or their respective parts, and the water or other surface being traversed up to a maximum height above such surface equal to 100% of the overall width of the WIG craft" [IMO DE44/17 WIG correspondence Group].

   WIG is therefore related to marine transport and their safety must relate to maritime rules. IMO is mandated internationally to set up international rules and regulations for marine dynamic supported craft and high-speed craft, including WIG. These are then incorporated into regulations issued by national authorities from the countries that form the IMO and maritime classification societies design rules that are used to control design of ships and other marine vehicles.

   We can only design and construct a WIG according to the IMO "Safety Code for WIG Craft" at present as no other regulations have been issued on an international basis to date.

   If a WIG is designed to be capable of free flight above the GEZ, then the requirements of ICAO will have to be met, the craft then being designed as a (sea) plane.

2. *Classification of WIG*

   WIG designed according to IMO requirements can be subdivided into three types as follows:

   - "A" Craft not capable of operation without the ground effect.
   - "B" Craft capable to increase its altitude limited in time and magnitude outside influence of the ground effect in order to over fly a ship, an obstacle or for other purpose. The maximal height of such an "over flight" should be less than the minimal safe altitude of an aircraft prescribed by ICAO.
   - "C" Craft capable to take-off from the ground and cruise at an altitude that exceeds the minimal safety altitude of an aircraft prescribed by ICAO.

   In general DACC and DACWIG belong to "A" type, classic WIG and PARWIG belong to "B" type, and seaplanes and flying boats belong to "C" type. The International Maritime Organization (IMO) and International Civil Aviation Organization (ICAO) will therefore be responsible for jointly setting up the safety code of such craft operating in various operation modes.

   The fields of competency of IMO and ICAO are as follows:

	WIG craft types		
Operational modes	A	B	C
Competency			
1. Displacement	IMO	IMO	IMO
2. Transitional	IMO	IMO	IMO
3. Skimming	IMO	IMO	IMO
4. Take-off/landing	IMO	IMO	IMO
5. Surface effect-main operational mode	IMO	IMO	IMO
6. Fly over		IMO/ICAO	IMO/ICAO
7. Aircraft mode			ICAO

Supplementary Safety Criteria for DACWIG

Proposal has been put forward to IMO for some modifications to the regulations in [6] so as to satisfy additional characteristics of WIG types such as the DACWIG. The suggestions for brief supplementary rules are as follows [12, 13]:

The proposals here are derived mainly from experience with DACWIG, which is somewhat different from PARWIG (Ekranoplan) and DACC (dynamic air cushion craft) due to its relative flying height not being beyond the surface effect zone (as PARWIG), nor nearly sticking the water surface (as DACC), but $0 < \bar{h} < 0.3$.

(1) *Design cases*: Due to DACWIG and DACC amphibious capabilities that they can be operated on ground, sand, swamp, ice, snow and water surfaces, etc.

the performance analysis and subsequent operational permit envelopes should include all these different conditions.

(2) *Collision*: In case of potential collision with other objects occurring during its flight in the surface effect zone, the pilot generally performs an avoiding manoeuvre, either in flying mode or in air cushion mode, or makes an emergency stop to avoid the possible collision accident. DACWIG and DACC cannot make a “jump”, as might be taken by pilots of PARWIG. Therefore, the regulation for avoiding collision, requirements for navigation and lighting of DACC and DACWIG should be similar to conventional high-speed vessels.

However, since the speed of DACWIG and DACC is far higher than the conventional high-speed craft, seat belts for passengers will be mounted on the craft similarly to commercial aircraft, with safety belts provided for all seats.

(3) *Static stability*: A DACWIG flying at cruise velocity should have inherent static and dynamic stability. The craft should be designed without automatic control systems to improve the stability of craft under action of foreign interference (wind, waves, gust, etc.). Instead, the main-wing and side buoy configuration should provide stability through the captured air bubble effect as flying height is reduced. DACC will have static stability provided by the cushion system.

(4) *Passenger restraint*: On small/medium-size DACWIG up to 30 passengers should not be free to move around in the craft during flight, as transverse stability is relatively sensitive to weight transfer.

(5) *Accommodation and escape*: Since DACWIG will be operated at high speed, collision avoidance in flying or cushion-borne mode is crucial. The collision load for craft structure and equipment will be considered as an accidental case bearing in mind the need for the WIG to remain floating and if possible operational. Passenger evacuation should be provided to life rafts. The evacuation time and route, exit and means of escape, etc. have to be considered in case of fire or other emergency conditions as described in the IOM guidelines. It is suggested that the fire hazard area should be enclosed by fire-resistant or heat-insulated material in compliance with the requirements of IMO and classification societies. The design should as far as practical comply with the rules and codes for conventional high-speed craft for these aspects.

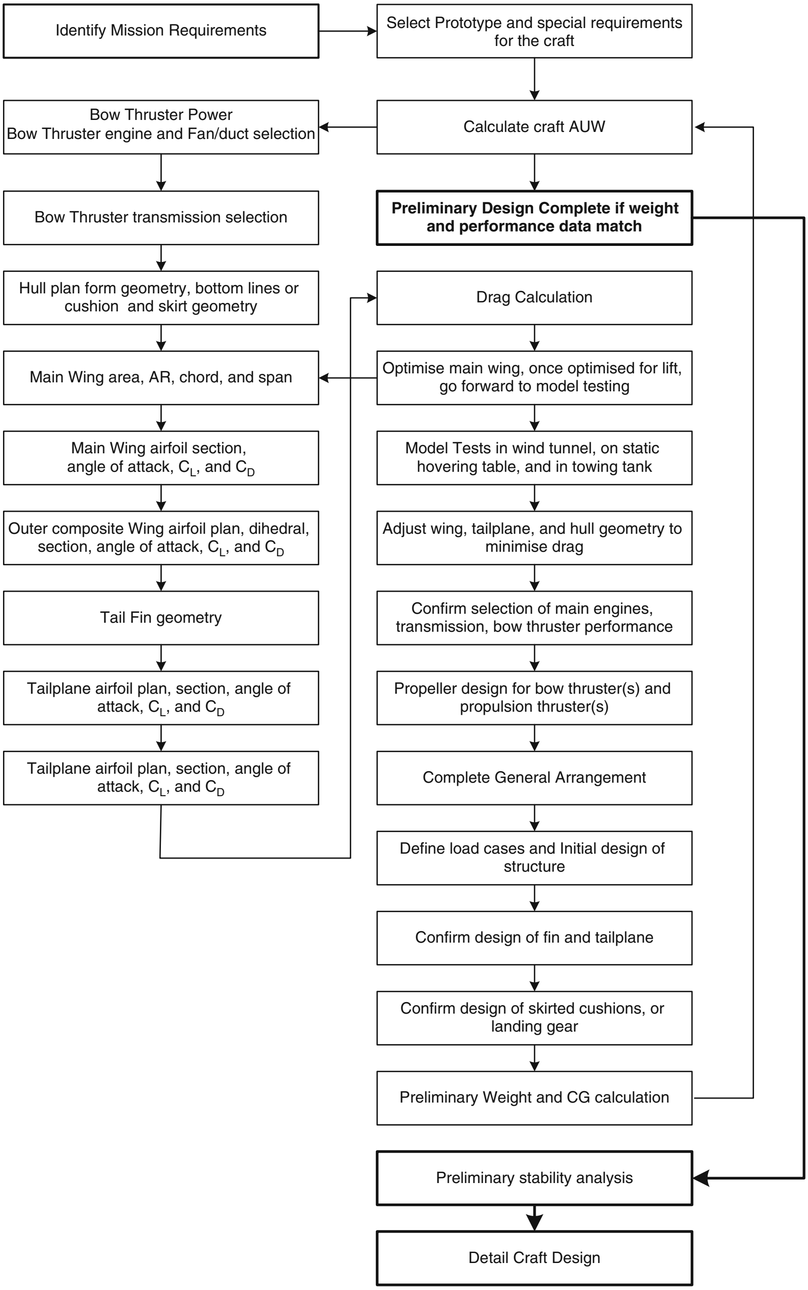
(6) *Anchoring, towing and berthing*: In order to save weight, the conventional anchor equipment for mooring high-speed craft may be reconsidered for WIG. For safety in emergency stop conditions, WIG can float with aid of a cone anchor to maintain heading into sea. Towing and berthing equipment will have to be included in the outfitting.

(7) *Redundancy and sparing of equipment*: The issues concerning redundancy of systems or machinery on high-speed craft for improving reliability have to be considered carefully on WIG. The ability to continue operation on one engine, where more than one is installed should be considered a requirement at least to enable boating to a safe harbour.

Setting Up a Preliminary Configuration

The determination of principal dimensions and overall preliminary design of a DACWIG may be carried out as follows (see also Table 13.1)

Table 13.1 WIG preliminary design flow chart



1. ***Determination of craft overall weight***

   Based on the mission specification of the design, the payload can be obtained, then

$$W = W_p/K_p \tag{13.5}$$

Where

W Weight overall of the craft
W_p Payload weight
K_p Coefficient of payload, in general, take $K_p = 0.2 - 0.3$

Typically a WIG should be able to achieve 20–30% of the overall take-off weight as a useable payload excluding fuel. The value will vary depending on the craft size, power plant chosen and structural material. It is suggested to try 25% as a first shot. Table 13.2 gives the percentage breakdown for Lun and Orlyonok, craft built with aluminium hulls and form the 1970/1980s design era to give some starting ideas.

Table 13.2 Weight breakdown (% W_o) of Russian WIG

Item	Weight	Lun	Orlyonok
1	Payload	20.6	12.2
2	Hull structure	44.0	54.5
2.1	hull	14.6	17.8
2.2	main wing	16.3	16.8
2.3	Tail in	2.3	2.9
2.4	Tailplane	3.6	3.9
2.5	Hydraulic ski	2.9	9.4
2.6	Other elements of hull structure	4.3	3.7
3	Power plant	11.8	13.4
3.1	Main engine	10.4	10.4
3.2	Equipments for main engine	1.4	3.0
4	Provisions, etc.	7.8	10.1
5	Fuel	15.8	9.8

2. ***Estimation of bow-thruster power and selecting the bow engines and type of bow thrusters***

   (1) *Rated power of bow thrusters*

   The rated power of bow thrusters can be defined based on the maximum static lift–thrust ratio of the prototype being used for comparison and specific thrust of the bow thrusters, as follows:

$$N_t = \frac{W}{n_t^{\eta_{Ls} K_t}} \tag{13.6}$$

where

N_t Rated power of each bow thruster
n_t Number of bow thrusters
η_{Ls} Maximum static lift thrust ratio, for DACWIG, $\eta_{Ls} = 4.5 - 7$for full-scale craft or 4.5–8 for models
K_t Specific thrust, where $K_t = f\left(C_p\right)$, C_p is the power coefficient of ducted propeller

$$C_p = N_t/\left(\rho_a n^3 D^5\right) \tag{13.7}$$

where

n propeller speed (rps)
D propeller diameter (m)

Figure 13.10 shows an example relation between specific thrust and power coefficient of ducted air propellers.

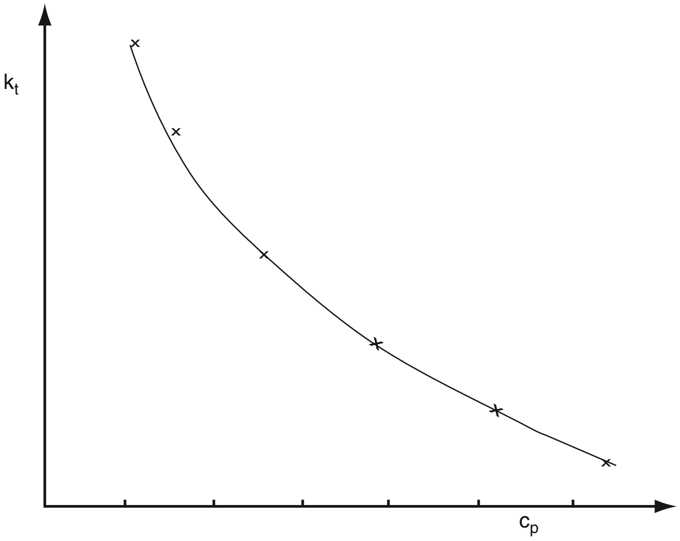


Fig. 13.10 K_t versus C_p from various ducted air propellers

(2) ***Selecting the type of bow engine and thrusters***

Based on the rated power, one can select an appropriate engine type and air propeller (see Chapters 11 and 12). References Chapter 6 [14] and Chapter 10 [7] introduce the theory and design of open and ducted air propellers. When installing ducted propeller systems on WIG, the following issues have to be taken into consideration:

Air propeller diameter: In general, a ducted air propeller is preferred for bow thrusters due to its ability to create higher cushion pressure under the main lifting wing. However, what diameter has to be chosen? In previous chapters, we have considered maximum. Thrust to be the controlling factor for designing the air propeller.

In fact, there are two separate criteria that are not unlike the requirements for ACV ducted propulsors. At low speed, the total pressure of the air-jet efflux from the air propeller H_j, rather than the free air thrust from the propeller, is most important. This suggests use of a small diameter high-solidity propeller system (four blades or more). At hump speed while accelerating into ground effect, it is important that the propulsors do have high total thrust including both propeller and duct thrust. This suggests that the duct system should be optimised for forward speeds around primary hump, having a normal airfoil section rather than a bell-mouth type with high mean line camber as on slower speed ACVs. Some experimentation will be necessary depending on the propellers available to the designer.

There is a strong relation between propeller thrust and diameter, but still not perfect. Figure 13.11 shows a relation between propeller diameter D_p, total pressure H_j and thrust of air propeller T_p for an example. It is found that an optimum D_p can be selected with both reasonable high-speed thrust and total pressure at zero speed. Higher total pressure equals higher cushion pressure and lift.

It is suggested that following points be considered for the ducted propulsors during general craft design:

- Choose several D_p alternatives for the propeller so as to compare both H_j and T_p as well as total thrust of the ducted propeller.
- Use the ratio A_p/A_f as a factor for selecting the diameter of propeller, where A_p is the frontal area of propeller and A_f frontal area of cushion air tunnel. The design ratio can be taken from existing prototypes and model test results. A useful starting point may be a value of 0.5.
- Consider the dynamic thrust-recovery coefficient η_{TD}. This strongly influences high-speed performance. Sometimes, a propeller/duct system can be designed with high static thrust, while only achieving lower η_{TD}. The most important factors influencing this are flight height $\bar{h}$, the angle of guide vanes β and relative distance between the propeller and main wing. Figure 13.12 shows η_{TD} versus relative flying height $\bar{h}$ and guide vane angle β. It is found that at higher $\bar{h}$, the greater the negative angle β the higher η_{TD} becomes. In addition a higher propeller position raises η_{TD} due to less interference of main wing on the airflow downstream of the propeller.

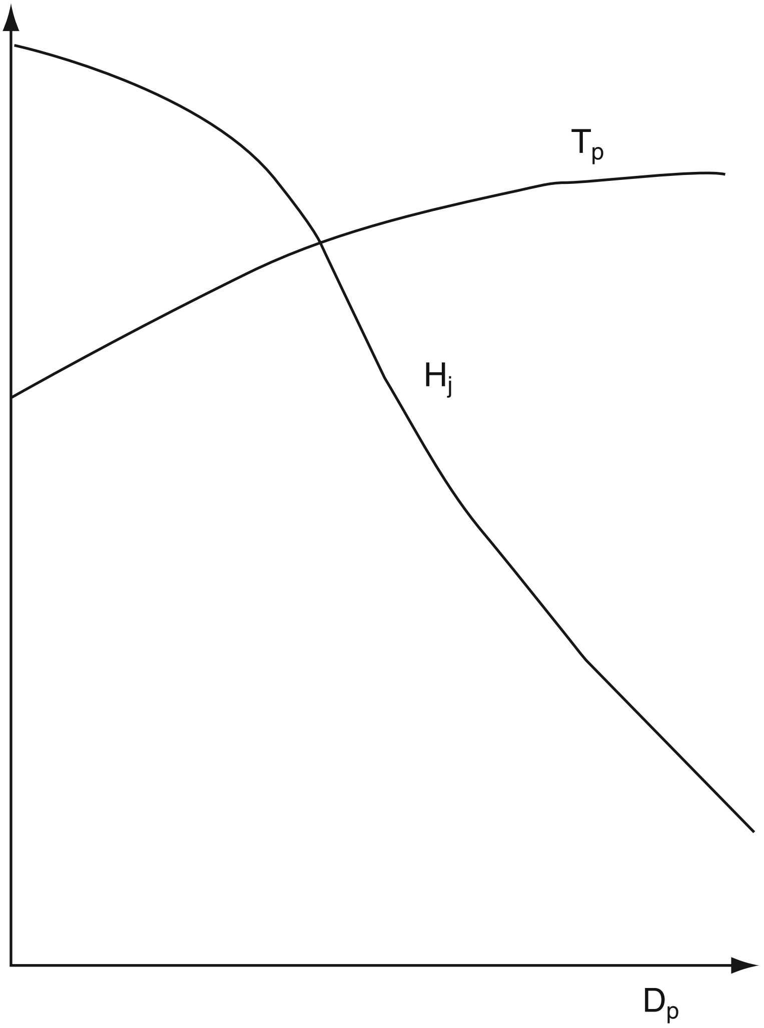


Fig. 13.11 Air propeller *T*, *D* and *H* relation

Selection of the ducted propulsor size, solidity, duct geometry, position relative to the main wing and guide vane system design is an extremely complicated task. One has to treat this as a trade-off problem, using the expertise introduced in previous chapters and considering both slow speed and high speed – particularly take-off performance of the craft.

3. *Overall powering assessment by comparison with existing craft*
   WIG power estimation for preliminary design may be made by comparison with other fast marine craft together with study results from earlier WIG

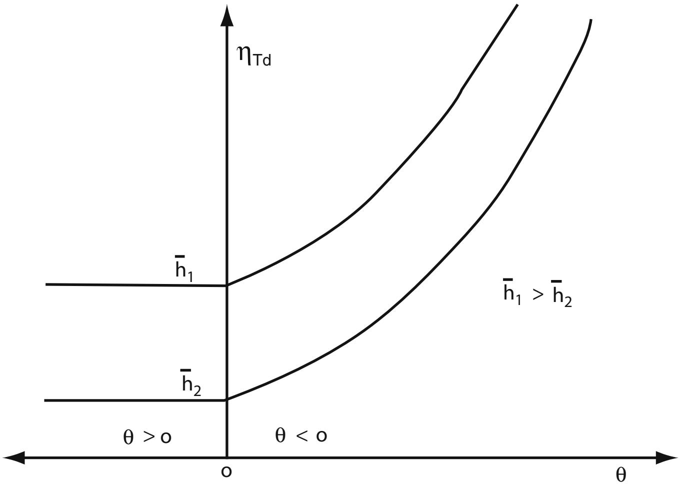


Fig. 13.12 η_{TD} versus relative flying height *h* and the angle of guide vane

designs. Sample data are included below. The reader is encouraged to assemble their own additional data into the same format so as to develop their own powering ground rules. Table 13.3 below presents the comparative transport efficiency of WIG with other high-speed craft, where

$\mathrm{Fn_d}$	Froude number, based on displacement, $= V_s / \left(g.W_o^{0.333}\right)^{0.5}$
W_e	Empty weight of craft (light weight)
W_o	All up weight
W_{us}	Useful load (payload together with fuel and consumables)
W_p	Payload
N	Full power of craft
N_p	Propulsive power at cruising speed, lift power can be shutdown (for PARWIG) or reduced (for DACC and DACWIG)
K_n	Propulsive efficiency coefficient based on total power, $= W_o V_s / N$
K_{np}	Propulsive efficiency coefficient based on propulsive power, $= W_o V_s / N_p$
T_e	Transport efficiency, $= W_p V_s / N = K_n W_p / W_o$
T_{eus}	Transport efficiency based on useful load, $= W_{us} V_s / N = K_n W_{us} / W_o$
T_{ep}	Transport efficiency based on propulsive power, $= W_p V_s / N_p = K_{np} W_p / W_o$
T_{epus}	Transport efficiency based on useful load and propulsive power, $= W_{us} V_s / N_p = K_{np} W_{us} / W_o$
	SFC Specific fuel consumption (kg/km × number passengers), $= Q_f N_p / V_s n_{pass}$
Q_f	Fuel consumption of engine (kg/kw h)
n_{pass}	Number of passengers

Table 13.3 Comparison of transport efficiency of WIG with other high-speed craft

	Semi-displacement ships	Catamaran	Hydrofoil	SES	ACV	WIG (PARWIG)	Airplane
Fn_d	1.5 – 2.5	2.0 – 2.8	2.5 – 3.5	2.5 – 4.0	3.5 – 5.0	10 – 15	20–35
W_e/W_o	0.60 – 0.70	0.65 – 0.80	0.70 – 0.80	0.55 – 0.65	0.55 – 0.70	0.55 – 0.72	0.55–0.65 (0.5 for $d > 5{,}000$ km)
W_{us}/W_o	0.30 – 0.40	0.20 – 0.35	0.20 – 0.30	0.35 – 0.45	0.30 – 0.45	0.28 – 0.45	0.35–0.45
W_p/W_o	0.25 – 0.35	0.15 – 0.30	0.15 – 0.25	0.33 – 0.40	0.28 – 0.40	0.20 – 0.35	0.15–0.30
K_n	5.0 – 9.0	4.5 – 8.0	5.0 – 6.0	5.5 – 7.5	2.5 – 4.5	5.5 – 10.5	5.0–9.0
K_{np}	5.5 – 10.0	5.0 – 9.0	5.5 – 6.7	6.0 – 8.5	2.8 – 5.0	8.0 – 15	6.0–10.0
T_e	1.6 – 2.6	1.0 – 1.8	1.0 – 1.5	1.6 – 3.2	0.6 – 1.5	1.5 – 2.0	1.0–2.0
T_{eus}	2.0 – 2.9	1.2 – 2.2	1.2 – 1.7	2.0 – 4.0	0.7 – 2.0	2.0 – 4.0	1.5–4.0 3.5 for $n_{pass} > 50$
T_{ep}	1.8 – 2.9	1.1 – 2.0	1.1 – 1.7	1.8 – 3.5	0.7 – 1.7	1.9 – 3.9	1.5–4.4
T_{epus}	2.2 – 3.2	1.3 – 2.4	1.3 – 1.9	2.2 – 4.4	0.8 – 2.2	2.9 – 5.8	2.2–5.0
SFC	0.022 – 0.036	0.033 – 0.060	0.040 – 0.065	0.023 – 0.045	0.030 – 0.10	0.022 – 0.049	0.020–0.050

From the table, it can be seen that

- The hydrodynamic efficiency can be written as $K_n = W_o \cdot V_s/N = K_{np} \cdot L/R$, where K_{np} is propulsion efficiency. The K_n for WIG is close to that of SES and catamarans, but at a higher Froude number Fn_d. In fact the hydrodynamic efficiency of WIG is similar to the aerodynamic efficiency of an airplane.
- The specific fuel consumption SFC is improved for WIG compared with other high-speed marine craft due to the ability to cruise at a much lower proportion of total installed power, the performance for larger WIG with modern engines (most WIG so far have been prototypes with engines that are low cost rather than high efficiency) should be higher than large transport aircraft of today.
- W_e/W_o of WIG is closer to that of an airplane than the other types of craft due to the lightweight aviation type of structure, equipment and engines used. Adopting heavier marine structure will have a direct impact on payload fraction and therefore transport efficiency. There is a trade-off for designers to analyse here, since structures are a significant portion of the construction cost.
- The economical efficiency of WIG can compete with an airplane. At short range, the lower fuel requirement for WIG can be translated into higher payload. At present, there is no precedent for long range WIG to compare with aircraft. Logically, the WIG higher payload capacity should further improve with increasing size, suitable for trans-oceanic routes, and the lower cruise power should maintain the advantage over aircraft, making them suitable for high-value freight delivery. This remains to be proven. Additionally, when the DACWIG configuration is utilised, an additional payload increment may be available, so further improving the efficiency, say by 10–15% at cruise speed into the range of 100–200 knots. Such speeds may be better suited to shorter routes up to 1,000 n.miles.

The construction cost of WIG will be higher than conventional high-speed craft and closer to aircraft due to higher powering and demand for lighter structure to improve payload fraction. The DACC/DACWIG cost price will be closer to marine practice as air cushion reduces take-off drag and powering.

WIG transport efficiency needs to improve further to give a clearer advantage compared with the alternative of using aircraft or fast marine ferries, to overcome the in-built market resistance to a new transport form. Recent research and prototype developments have pointed the way in this respect. Designers should therefore target improved aerodynamic efficiency compared to the existing data.

Figure 13.6 can be used for initial performance estimation. The aerodynamic efficiency of WIG first and second generations and an aircraft weighing 450 t is shown in this figure, where 1 – first-generation WIG, 2 – second-generation WIG, 3 – aircraft, K_{max} the maximum aerodynamic property, $\bar{h}$ the flying height and C the wing chord. Figure 13.7 shows the WIG weight composition compared with aircraft, where W_p and W_f are the payload and fuel weight, respectively, and W_0 craft take-off weight. This data may also be used as a starting point, bearing in mind modern structural techniques should improve on this. Figure 13.8 shows a comparison of WIG fuel consumption with aircraft, where R represents craft range.

From these figures, second-generation WIG can be seen to compete with jumbo jet flying at 10,000 m altitude, where aerodynamic drag is lower. These data are useful as a starting point for designing larger WIG craft. Modern engines should be able to give an improved performance, either longer range or lower fuel fraction for a given range.

Once the designer has made an assessment of the target K_n and K_{np}, a first definition of installed power for cruising and takeoff can be made. This can be checked with the bow-thruster powering assessed earlier and the necessity for separate cruising propulsors evaluated.

4. ***Selecting type of power transmission, directly or via gearbox, flexible coupling and intermission shaft***

   At this point, the designer will wish to select the overall configuration for the power system, including the number of engines and propellers and their location.

   If the craft is a small one, say for taxi service, it is likely that a single engine would be selected and transmission shafts used to connect the engine, mounted in the central hull with the propellers. Such a system is realistic for a classic WIG configuration with propellers mounted above the trailing edge of the main wing. A DACWIG or DACC with propellers mounted in front of the main wings will require twin engines mounted on the wings to minimise the transmission length. The alternative is a single or multiple engines within the central hull and geared shaft or belt drive out to the propeller. This configuration adds some weight and complexity, but may give improved aerodynamics.

   Larger craft using gas turbine engines are easier to design into a system, since the engine will be mounted in a nacelle inside the propeller duct or on a pylon ahead of its propeller.

5. ***Determination of main-wing chord***

   We suggest that designers select a range of spans of the main lifting wing so as to check the effect of aspect ratio and compare the aerodynamic properties of the different wings.

   Where a classic WIG is being designed, the designer will want to investigate the effect of anhedral and swept/tapered geometries to provide optimum air bubble capture at speeds up to take-off, including the use of trailing edge flaps. The aim should be to develop an air cushion pressure supporting 50–70% of craft weight below 100 kph for larger craft and 50–70 kph for smaller craft. This will reduce hump drag and allow smoother take-off in the speed range of 120–140 kph for larger craft and 60–80 kph for smaller craft.

The main-wing chord has to be considered carefully so as to optimise air injection of the bow thruster and static lift–thrust ratio for bow-thrusters-assisted craft (PARWIG, DACWIG and DACC). It is suggested that the minimum beam of the wing air channel $d_P/B_a = 0.5\text{-}0.7$, where D_p is the diameter of propeller and B_a is the width of air tunnel (i.e. main wing). The maximum wing span will also be restricted by permissible maximum width of the craft.

Another criterion for selecting the width of the air tunnel is A_f/A_p, where A_f is the frontal projected area of air tunnel and A_p is the area of propeller disc. Then

$$A_f = B_a \cdot H_b$$

where H_b is the height between the craft base plane and main-wing leading edge (for a wing without anhedral). It may be seen that H_b is a function of the design angle of attack of the main wing.

$$A_p = (\pi D_p^2)/4$$

The ratio of A_f/A_p is an important parameter that affects the air-jet formation and cushion pressure. In general, it is recommended that

$$A_f/A_p = 1.5\text{-}2.5$$

6. *Determination of the surface area of the main wing*

The area providing the lift for the craft in air cushion mode (whether dynamic or thruster assisted) includes the surface area of the main support wing and also that under the main hull and side buoys. This area may also be referred to as the equivalent wing area.

The design hovering height, either static for thruster-assisted craft or at chosen design speed for classic WIG, and the wing area can be found from Chapter 4 and cushion static pressure can be found as

$$P_c = f(\bar{h}) \cdot q_j \qquad (13.8)$$

where

$q_j = 0.5\rho_a V_j^2$	The velocity head of air jet (pascals) of incoming airflow
$P_c = kq_j$	$k = 1.05\text{-}1.15$ for a channel with $A_f/A_p = 2.5\text{-}1.5$ may be used as a start point for calculations

$$\text{Now} \quad q_j = T_p/A_p \qquad (13.9)$$

where

A_p	The area of propeller disc
T_p	Static thrust of propeller

Coefficient k will vary greatly with geometry of the cushion cavity and main wing, together with the position of the bow thrusters if present. It is necessary to carry out experimental work to determine the value accurately.

For non-assisted WIG, V_j is simply the airspeed and resultant H is the dynamic head. The relevant capture area will be the presented area bounded by the ground plane, the wing leading edge and the hull and side buoys. At forward speeds, a DACWIG benefits from the captured air bubble as well as the thruster's injection, the forward speed gradually increasing the efficiency of the thruster generated air cushion.

$$\text{Now} \qquad S_c = (W/P_c) \cdot \xi_1 \cdot \xi_2 \tag{13.10}$$

ξ_1	The coefficient of pressure non-uniformity of air cushion, =0.95–1.0
ξ_2	Coefficient of Coanda effect, =1.05–1.15

It may be noted that the cushion area S_c will include the lift area under the hull and side buoys as well as the main lifting wing, therefore

$$S_c = S_{c1} + S_{c2} + S_{c3} \tag{13.11}$$

Where

S_{c1}	Horizontal area under the wing surface
S_{c2}	Horizontal area under the hull surface
S_{c3}	Horizontal area under the side buoys

The craft width overall in the case of having two air tunnels is B_m
Where

$$B_m = 2B_c + b_h + 2(b_{sb}/2) \tag{13.12}$$

B_c	Cushion beam or main-wing half span
b_h	Hull beam
b_{sb}	Sidewall or side buoy beam

In assessing area for the cushion, half of the width of each side buoy is used since the outer half has a sharply decaying pressure towards ambient if the side buoys are designed with a central keel and planing surfaces with deadrise, as is normal.

The craft beam can be assessed once the geometry for the main wings has been selected, whether rectangular or trapezoidal, and the average chord determined. Once this is known and the proposed hull and side buoy widths selected, the overall beam can be determined.

7. ***Length and width of main hull***

   The length L_h and the beam b_h as well as the height H_h can be obtained once a sketch of the craft general arrangement for passenger cabin, navigation cabin has been prepared.

   The minimum permissible distance between the bow air propeller disc lower tip and the static water surface at the bow so as to prevent possible water impact on the propeller blades in hull-borne operation can be determined based on the design take-off and landing sea state, and checked against the desired cruising height and sea state. It is recommended that the clearance of lower tip of a propeller or propeller duct should always be larger than 0.5 m for bow propellers.

   The sidewalls beam b_sb can be obtained by the calculation of craft static draft.

8. ***Chord length C and aspect ratio (AR) of the equivalent wing***

$$C = S_\mathrm{c}/B_\mathrm{m} \tag{13.13}$$

$$\mathrm{AR} = B_\mathrm{m}/C \tag{13.14}$$

9. ***Wing profile***

   The main-wing profile can then be selected by reference to Chapter 5.

10. ***Aerodynamic lift coefficient $C_y$and aspect ratio of the main wing***

    The aerodynamic lift coefficient C_y has a great influence on the selection of optimum angle of attack of the wing for flying mode operation. Larger C_y can decrease the total area of wing (including the area of composite wing), but with a penalty of reducing the longitudinal stability. A useful starting point is to make reference to existing craft and select a suitable C_y. Examples of existing WIG C_y are listed in Table 13.4 .

    Figure 13.13 shows the relation between the C_y, AR and the Froude number $\mathrm{Fn_d}$; it is found that the average tendency of various parameters mentioned above is at higher $\mathrm{Fn_d}$, C_y becomes smaller, AR larger. This is reasonable in the view of aerodynamic characteristics and stability, so the figure can be referenced in the design of WIG to choose C_y and AR.

11. ***Determination of area and some design considerations for composite wing and tailplane***

    When using a composite wing outboard of the side buoys to give additional stability and controllability, the composite wing area S_cw can be estimated as follows:

$$W_0 = 0.5\rho_\mathrm{a}v^2C_yS_\mathrm{eq} \tag{13.15}$$

Table 13.4 Aerodynamic lift coefficients of some existing WIG (estimated values)

Craft type	KM (WIG)	Spasatel (WIG)	Orlyonok (WIG)	SM-6 (WIG)	Strizh (WIG)	Amphistar (DACC)	Volga-2 (DACC)	Swan (DACWIG)
Country	Russia	Russia	Russia	Russia	Russia	Russia	Russia	China
Weight (t)	540	400	140	26	1.8	2.2	2.5	7.2
Cruising speed (km/h)	500	480	350	360	185	150	120	130
Cruising speed (m/s)	138.9	133.3	97.2	100	51.4	41.6	33.3	36.1
Wing area, S_c(m)	662.5	?	307	73.8	18.18	32	43.89	?
AR = B_c/C	2.0	?	3.07	2.86	2.47	1.10	1.36	?
Wing span, B_c (m)	37	44.0	31.5	14.8	6.7	5.92	7.73	?
Chord length, $C = S_c/B_c$ (m)	17.9	?	9.74	4.99	2.71	5.37	5.68	?
Fn	15.5	?	13.6	18.54	14.87	11.6	9.12	?
C_y*	0.676	?	0.778	0.56	0.6	0.636	0.82	?

$*C_y = \frac{W}{0.5\rho_a v^2 S_c}$

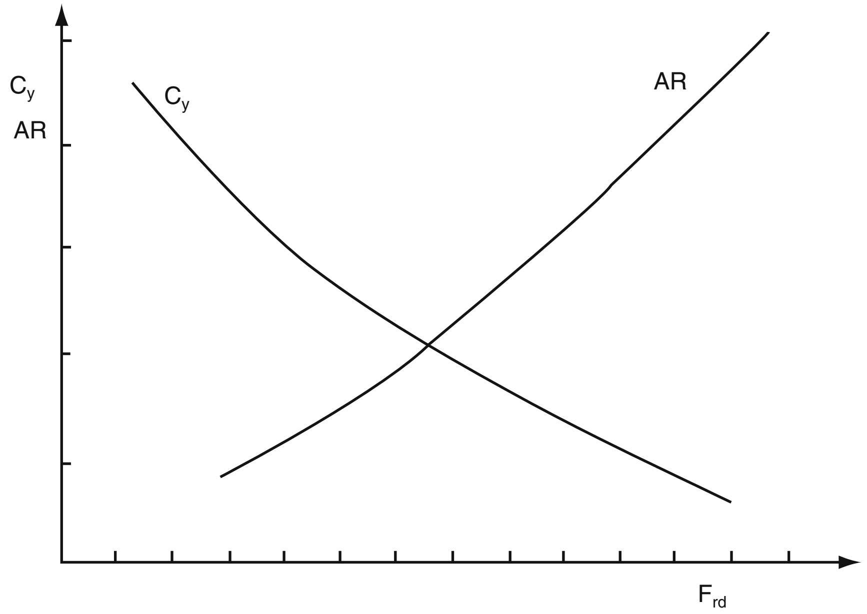


Fig. 13.13 C_y versus Fn_d, and AR versus Fn_d from various WIG craft

$$S_{eq} = S_c + S_{cw} + S_{tw} \qquad (13.16)$$

where

W	Craft weight
S_c	Area of main wing, hull and side buoys
S_{cw}	Area of composite wing

It is assumed here that normally the tailplane or horizontal tail wing is designed purely as a stability and control surface and will not contribute to lifting the craft. The term S_{tw} in Equation (13.16) can therefore normally be left out. The sizing of the tail wing (stabiliser and elevators) can be started as follows:

S_{tw}	Area of horizontal tail wing

At first step of preliminary design, we can take

$S_{tw} = (S_c + S_{cw})/K_{tw}$ as the first approximation, where
$K_{tw} = 1.15\text{-}1.3$ is the coefficient taken from prototype.

This is a conservative estimate based on experience with DACWIG. The tailplane can be reduced by lengthening the hull so that it has a greater lever arm. It is best to make an assessment of the needed moment at take-off and cruise speeds, and then try a number of combinations of lever arm and sizing until a satisfactory combination is achieved.

Then we have to consider the design of the composite wing as follows:

Area and foldability: The aerodynamic efficiency of a composite wing is higher than that of the main wing due to its higher aspect ratio, so designers will make the area and span of composite wing as large as possible, so long as the main-wing area is large enough for static hovering. However, since a large span composite wing will negatively influence craft slow speed manoeuvrability, it is possible to make the composite wing foldable for smaller craft, similar to the Russian WIG I-Volga-2, Fig. 13.14. The composite wing can be folded when floating, and on cushion, particularly for operation over ground.

Fig. 13.14 IVolga

Longitudinal position: There are two design possibilities for the longitudinal position of the composite wing as follows:

- Composite wing located near the CG of the craft, as shown in Fig. 13.15. Since the aerodynamic efficiency of the composite wing is higher due to its high aspect ratio, location here will influence the overall craft aerodynamic properties less during large trimming angles.
- Located at the rear part of main wing (Fig. 2.36). This design is to improve longitudinal force balance and decrease the horizontal tail wing area.

Figure 13.15 shows three-view drawing of WIG with forward composite wing. Key to Figure 13.15 is as follows:

1. Main fuselage/hull
2. Main wing
3. Tailplane
4. Nose of fuselage
5. Bow thruster
6. Cruising engines
7. hull planing surface
8. Wing flaps
9. Outer stabiliser wing (composite wing)
10. Tail fin
11. Rudder
12. Elevator

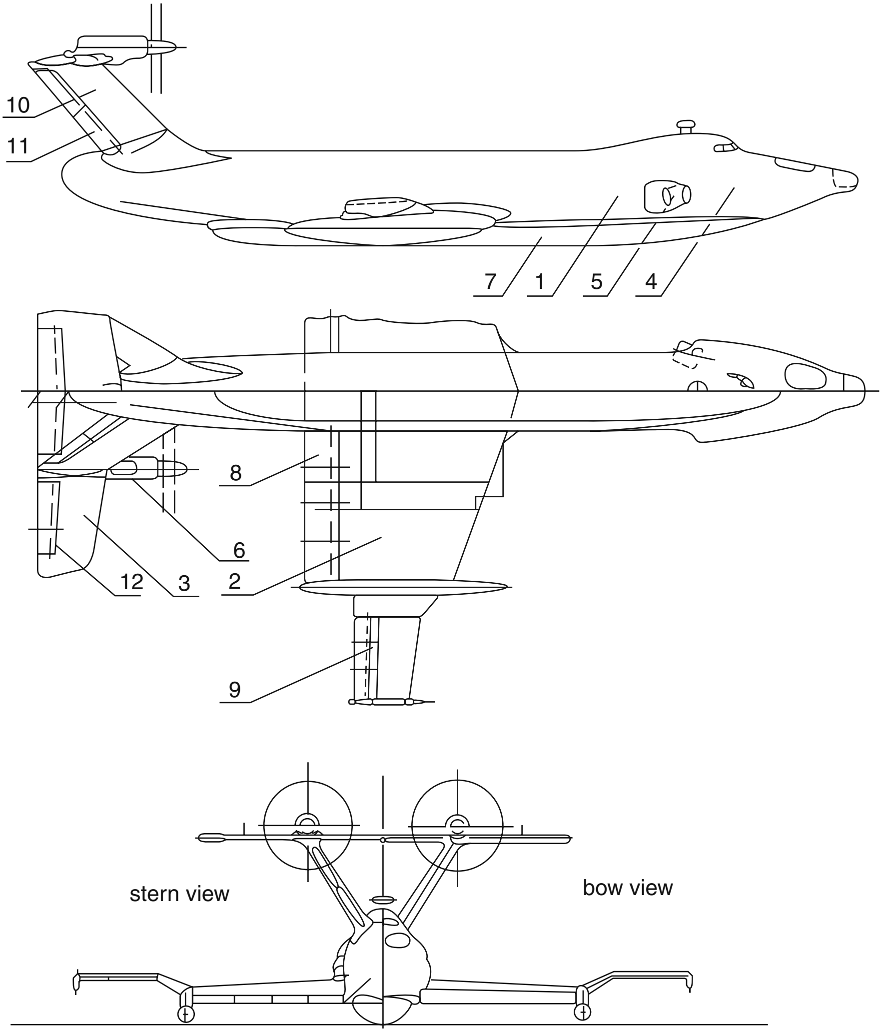


Fig. 13.15 Composite wing located near craft CG

Vertical position: The advantages of composite wings have been described in the previous chapters, including increasing lift, aerodynamic efficiency, and decreasing air drag. This is due to using fully the residual energy of the tip vortex around the side buoys. However, the interference of transverse airflow from the air channel will reduce the aerodynamic efficiency of the composite wing, particularly in case of location at rear of the side buoy and in lower position. In this case, the transverse and upward airflow from the air channel will be intensified, particularly in case of lower flying height and large trim angle. Such flow will cause a decrease of lift–drag ratio, and sometimes lead to separation of the flow on the composite wing. This is a serious problem and may be improved with aid of following measures:

- Using wing fences located on the lower surface of the composite wing (Fig. 7.29), to prevent transverse flow
- Positive dihedral angle of the composite wing for reducing the influence of transverse airflow
- Decreasing the installed angle of attack of the composite wing so as to defer the separation angle of composite wing at large trimming angle

All such measures should be validated by wind-tunnel tests for the proposed design.

12. ***Determination of angle of attack of main wing and composite wing***

The influence of wing profile on the aerodynamic characteristics of WIG was described in Chapter 5, Designers can choose reasonable wing profiles with aid of this chapter together with the referenced standard texts for low-speed airfoils, for example references in Chapters 3 [8], 6 [5, 6, 14] and 10 [7].

The installed angle of attack of both main wing and composite wing can be specified based on the aerodynamic characteristics of the wing, using the selected C_y and wing profile to check the total lift.

13. ***Determination of the longitudinal location of composite wing, parameters and location of horizontal tail stabiliser***

With aid of Chapters 5 and 6, the location of the composite wing and geometrical parameters, as well as the tailplane location can be determined by the following equations.

Longitudinal force balance equation:

$$L_{\mathrm{mw}} \cdot l_{\mathrm{mw}} + L_{\mathrm{cw}} \cdot l_{\mathrm{cw}} + L_{\mathrm{tw}} \cdot l_{\mathrm{tw}} + T_{\mathrm{pb}} \cdot l_{\mathrm{pb}} + T_{\mathrm{pa}} \cdot l_{\mathrm{pa}} + R_{\mathrm{a}} \cdot l_{\mathrm{a}} = 0 \quad (13.17)$$

where

L_{mw}	Main wing lift including the lift due to the hull and sidewalls of craft, then $L_{\mathrm{mw}} = 1/2\rho_{\mathrm{a}} V^2 S_{\mathrm{c}} C_y$
l_{mw}	Horizontal distance between the aerodynamic centre of main wing (including the hull and sidewalls) and CG of the craft
L_{cw}	Composite wing lift
l_{cw}	Horizontal distance between the aerodynamic centre of composite wing and CG
L_{tw}	Horizontal tail stabiliser lift
l_{tw}	Horizontal distance between the aerodynamic centre of the horizontal tail and CG
T_{pb}	Bow propellers thrust
l_{pb}	Perpendicular distance between thrust of bow propellers and CG of craft
T_{pa}	Stern propellers thrust

L_{pa}	Perpendicular distance between the thrust of stern propellers and CG of the craft
R_{a}	Air profile drag of the craft
l_{a}	Perpendicular distance of the centre of action of air drag, from the CG

At the first approximation, the influence of propeller thrust and air drag as well as airflow down-wash can be neglected, as these can be determined in the during design optimisation, then

$$T_{\mathrm{pb}} \cdot l_{\mathrm{pb}} + T_{\mathrm{pa}} \cdot l_{\mathrm{pa}} + R_{\mathrm{a}} \cdot l_{\mathrm{a}} = 0 \tag{13.18}$$

So that Equation (13.17) becomes

$$L_{\mathrm{mw}} \cdot l_{\mathrm{mw}} + L_{\mathrm{cw}} \cdot l_{\mathrm{cw}} + L_{\mathrm{tw}} \cdot l_{\mathrm{tw}} = 0 \tag{13.19}$$

The CG of the craft has to be located near the centre of action of static hovering lift to satisfy the longitudinal force balance when hovering static (during landing and launching of craft). A starting assessment will be

$$X_{\mathrm{g}} = (0.40\text{-}0.48) \cdot C \tag{13.20}$$

X_{g} is the horizontal distance calculated from the leading edge of the main wing, varied according to the position of the flaps and guide vanes after the bow propeller. A preliminary weight distribution can be prepared to test the position of X_{g} for the chosen craft geometrical configuration.

Another equation that has to be complied with is the longitudinal stability equation, that is

$$\begin{aligned}(S_{\mathrm{mw}} + S_{\mathrm{cw}} + S_{\mathrm{tw}})\,\bar{X}_{F\vartheta}\,C_y^{\vartheta} = {} & C_{\mathrm{ymw}}^{\vartheta} X_{\mathrm{F}\vartheta\mathrm{mw}} S_{\mathrm{mw}} + C_{\mathrm{ycw}}^{\vartheta} X_{\mathrm{F}\vartheta\mathrm{cw}} S_{\mathrm{cw}} \\ & + C_{\mathrm{ytw}}^{\vartheta} X_{F\vartheta\mathrm{tw}} S_{\mathrm{tw}} \cdot k_{\mathrm{q}}\end{aligned} \tag{13.21}$$

Where $C_{\mathrm{ymw}}^{\alpha} = C_y^{\alpha} k_{\alpha}$

At first approximation, take $k_{\alpha} = 1$ and $k_{\mathrm{q}} = 1$ and $\bar{X}_{\mathrm{F}\vartheta} - \bar{X}_{\mathrm{g}} = 0.03\text{-}0.08$

Since all of the values in Equations (13.18) and (13.21) are given except l_{cw} and l_{tw}, then the defined values l_{cw} and l_{tw} can be calculated. It should be noted that the influence of the air-jet blown from the bow thruster into the air channel on the centre of aerodynamic lift (CA) of main wing has to be considered. The CA cannot be taken from the aerodynamic characteristic table of the wing section, but it can be taken from a prototype, model test results or analysis.

Procedure for Overall Preliminary Design

Once the WIG preliminary configuration has been set up and perhaps a cycle or two carried out to test adjustments, the preliminary design itself may be started. At this point, general arrangements for the proposed craft should be prepared, preliminary structural design carried out and weight estimates prepared, so that more accurate analysis of craft lift, drag and powering can be completed.

The procedure for overall preliminary design is as follows:

1. Layout of lines for the hulls and side buoys
2. Layout of general arrangement
3. Select the stern power plant (cruise engine(s) for thrusters assisted or main engines for classic WIG)
4. Select bow thrusters power plant, location and transmission
5. Structure preliminary design
6. Calculation of weight of the craft
7. Drag calculations for the craft at various operation modes
8. Air propeller design
9. Appendage design (including horizontal and vertical rudders, as well as landing pads and air inflatable bag as side buoy)

This design work is based on the selection of dimensions and characteristics described in the section above "Setting up a preliminary Configuration" and follows a similar approach as used for propeller-driven aircraft and to some extent amphibious ACVs.

Once the preliminary design is available, the first pass at aerodynamic performance of the WIG can be carried out. It is likely that this work will require adjustments to the configuration and so the preliminary design may have to be revisited, or possibly a reconsideration of the functional requirements taken into account

The block diagram for the overall preliminary design is as shown in Table 13.1; this includes the design adjustment loops for optimisation.

Determination of WIG Aerodynamic and Hydrodynamic Characteristics

There is no self-contained analytical method available at present to determine the aerodynamic and hydrodynamic configuration of a WIG, due to the complicated airflow related to both the surface effect and air-jet effect on the craft main wings. Designers generally use both theoretical calculation and experimental investigation to find a reasonable compromise of aerodynamic and hydrodynamic configuration. Based on the preliminary design determined above, the aerodynamics and hydrodynamics of the design can be analysed by

(1) Select a suitable prototype and reference data, if available, to make a preliminary assessment of the new craft performance and adjust the configuration.

(2) Develop the aerodynamic configuration of the WIG, by carrying out model tests to determine the characteristic data specific to the new design.

A summary of possible experimental investigations into aerodynamics and hydrodynamics of WIG can be found in Table 10.5.

In general, we take six steps as follows:

- Model test on rigid table to study the static hovering performance of the craft (if necessary) to define the geometry and size of air tunnel, the arrangement of bow thrusters, etc.
- Catapult test of WIG to study the both longitudinal and transverse stability of an unpowered model craft
- Wind-tunnel test to study the aerodynamic properties
- Radio-controlled free flight model tests on open water area to study both aerodynamic and hydrodynamic properties and stability, as well as take-off ability of the craft model
- Towing tank test to study the craft performance both in calm water and waves
- Manned control test craft to study the craft performance at larger scale, if the design is for a very large craft

(3) Refinement of the principal dimensions followed by detailed design of the DACWIG.

WIG Detailed Design

WIG detailed design should follow a similar path to design of an aircraft. Once the initial performance has been established based on preliminary design and machinery selection has been confirmed, a detailed design of the main structure can be carried out.

Structural design for WIG will be based on two main analysis cases, take-off and cruise speed, and a series of appropriate load cases defining the operational envelope of craft operating weights and environmental loadings associated with these two analysis cases.

The aerodynamic component of structural design can be completed following the methods of references such as reference Chapter 10 [3], while the marine aspects should be carried out following normal practice in naval architecture, with reference to works such as references Chapters 3 [7], and 7 [6].

Design of machinery systems will largely follow aircraft practice, a useful text for which is Chapter 11 [1].

Following primary structural design, assessment of intact and damaged floating stability, and development of a detailed weight take-off, the data necessary to build wind tunnel and towing tank models will be available. The results of these tests will be able to confirm the earlier projected performance data.

Following confirmation of the overall craft design, outfitting design can begin, and as the equipment HVAC, lighting and other ancillary systems are added, their weight data can replace the nominal figures used as a basis for structural design.

Finally the construction methodology for the craft can be completed, including moulds for elements to be formed in fibre-reinforced plastics and tooling for aluminium structures.

In parallel with detailed design, the initial commercial proposal for the craft can be refined based on detailed costs estimates once construction methodology has been selected. The cost estimates should be refined based on assessment of the complete project delivery including prototype development, testing and certification, preparation of operating guidelines and manuals. Most importantly contingencies should be applied to both cost estimates and schedules. If the craft is a prototype, then particular care is needed to accommodate "unknowns" into the schedule and allow for schedule delays while bugs are sorted out. Since the time is cost, it is important to have a flexible commercial arrangement with the supporting engineering and construction organisations, so as not to incur excessive costs due to schedule delay as a craft is refined into a commercial proposition.